# 1 Introduction

## 1.1 PURPOSE OF THE COURSE

The objectives of a first-year, one-semester graduate course in electric power generation, operation, and control include the desire to:

1. Acquaint electric power engineering students with power generation systems, their operation in an economic mode, and their control.
2. Introduce students to the important "terminal" characteristics for thermal and hydroelectric power generation systems.
3. Introduce mathematical optimization methods and apply them to practical operating problems.
4. Introduce methods for solving complicated problems involving both economic analysis and network analysis and illustrate these techniques with relatively simple problems.
5. Introduce methods that are used in modern control systems for power generation systems.
6. Introduce "current topics": power system operation areas that are undergoing significant, evolutionary changes. This includes the discussion of new techniques for attacking old problems and new problem areas that are arising from changes in the system development patterns, regulatory structures, and economics.

## 1.2 COURSE SCOPE

Topics to be addressed include:

1. Power generation characteristics.
2. Economic dispatch and the general economic dispatch problem.
3. Thermal unit economic dispatch and methods of solution.
4. Optimization with constraints.
5. Using dynamic programming for solving economic dispatch and other optimization problems.

6. Transmission system effects:
   a. power flow equations and solutions,
   b. transmission losses,
   c. effects on scheduling.
7. The unit commitment problem and solution methods:
   a. dynamic programming,
   b. the Lagrange relaxation method.
8. Generation scheduling in systems with limited energy supplies.
9. The hydrothermal coordination problem and examples of solution techniques.
10. Production cost models:
    a. probabilistic models,
    b. generation system reliability concepts.
11. Automatic generation control.
12. Interchange of power and energy:
    a. interchange pricing,
    b. centrally dispatched power pools,
    c. transmission effects and wheeling,
    d. transactions involving nonutility parties.
13. Power system security techniques.
14. An introduction to least-squares techniques for power system state estimation.
15. Optimal power flow techniques and illustrative applications.

In many cases, we can only provide an introduction to the topic area. Many additional problems and topics that represent important, practical problems would require more time and space than is available. Still others, such as light-water moderated reactors and cogeneration plants, could each require several chapters to lay a firm foundation. We can offer only a brief overview and introduce just enough information to discuss system problems.

## 1.3 ECONOMIC IMPORTANCE

The efficient and optimum economic operation and planning of electric power generation systems have always occupied an important position in the electric power industry. Prior to 1973 and the oil embargo that signaled the rapid escalation in fuel prices, electric utilities in the United States spent about 20% of their total revenues on fuel for the production of electrical energy. By 1980, that figure had risen to more than 40% of total revenues. In the 5 years after 1973, U.S. electric utility fuel costs escalated at a rate that averaged 25%

compounded on an annual basis, The efficient use of the available fuel is growing in importance, both monetarily and because most of the fuel used represents irreplaceable natural resources.

An idea of the magnitude of the amounts of money under consideration can be obtained by considering the annual operating expenses of a large utility for purchasing fuel. Assume the following parameters for a moderately large system.

Annual peak load: 10,000 MW

Annual load factor: 60%

Average annual heat rate for converting fuel to electric energy: 10,500 Btu/kWh

Average fuel cost: \$3.00 per million Btu (MBtu), corresponding to oil priced at 18 \$/bbl

With these assumptions, the total annual fuel cost for this system is as follows.

Annual energy produced: $10^7$ kW $\times$ 8760 h/yr $\times$ 0.60 = 5.256 $\times$ $10^{10}$ kWh

Annual fuel consumption: 10,500 Btu/kWh $\times$ 5.256 $\times$ $10^{10}$ kWh
= 55.188 $\times$ $10^{13}$ Btu

Annual fuel cost: 55.188 $\times$ $10^{13}$ Btu $\times$ 3 $\times$ $10^{-6}$ \$/Btu = \$1.66 billion

To put this cost in perspective, it represents a direct requirement for revenues from the average customer of this system of 3.15 cents per kWh just to recover the expense for fuel.

A savings in the operation of this system of a small percent represents a significant reduction in operating cost, as well as in the quantities of fuel consumed. It is no wonder that this area has warranted a great deal of attention from engineers through the years.

Periodic changes in basic fuel price levels serve to accentuate the problem and increase its economic significance. Inflation also causes problems in developing and presenting methods, techniques, and examples of the economic operation of electric power generating systems. Recent fuel costs always seem to be ancient history and entirely inappropriate to current conditions. To avoid leaving false impressions about the actual value of the methods to be discussed, all the examples and problems that are in the text are expressed in a nameless, fictional monetary unit to be designated as an "R."

## 1.4 PROBLEMS: NEW AND OLD

This text represents a progress report in an engineering area that has been and is still undergoing rapid change. It concerns established engineering problem areas (i.e., economic dispatch and control of interconnected systems) that have taken on new importance in recent years. The original problem of economic

dispatch for thermal systems was solved by numerous methods years ago. Recently there has been a rapid growth in applied mathematical methods and the availability of computational capability for solving problems of this nature so that more involved problems have been successfully solved.

The classic problem is the economic dispatch of fossil-fired generation systems to achieve minimum operating cost. This problem area has taken on a subtle twist as the public has become increasingly concerned with environmental matters, so that "economic dispatch" now includes the dispatch of systems to minimize pollutants and conserve various forms of fuel, as well as to achieve minimum costs. In addition, there is a need to expand the limited economic optimization problem to incorporate constraints on system operation to ensure the "security" of the system, thereby preventing the collapse of the system due to unforeseen conditions. The hydrothermal coordination problem is another optimum operating problem area that has received a great deal of attention. Even so, there are difficult problems involving hydrothermal coordination that cannot be solved in a theoretically satisfying fashion in a rapid and efficient computational manner.

The post World War II period saw the increasing installation of pumped-storage hydroelectric plants in the United States and a great deal of interest in energy storage systems. These storage systems involve another difficult aspect of the optimum economic operating problem. Methods are available for solving coordination of hydroelectric, thermal, and pumped-storage electric systems. However, closely associated with this economic dispatch problem is the problem of the proper commitment of an array of units out of a total array of units to serve the expected load demands in an "optimal" manner.

A great deal of progress and change has occurred in the 1985–1995 decade. Both the unit commitment and optimal economic maintenance scheduling problems have seen new methodologies and computer programs developed. Transmission losses and constraints are integrated with scheduling using methods based on the incorporation of power flow equations in the economic dispatch process. This permits the development of optimal economic dispatch conditions that do not result in overloading system elements or voltage magnitudes that are intolerable. These "optimal power flow" techniques are applied to scheduling both real and reactive power sources, as well as establishing tap positions for transformers and phase shifters.

In recent years the political climate in many countries has changed, resulting in the introduction of more privately owned electric power facilities and a reduction or elimination of governmentally sponsored generation and transmission organizations. In some countries, previously nationwide systems have been privatized. In both these countries and in countries such as the United States, where electric utilities have been owned by a variety of bodies (e.g., consumers, shareholders, as well as government agencies), there has been a movement to introduce both privately owned generation companies and larger cogeneration plants that may provide energy to utility customers. These two groups are referred to as independent power producers (IPPs). This trend is

coupled with a movement to provide access to the transmission system for these nonutility power generators, as well as to other interconnected utilities. The growth of an IPP industry brings with it a number of interesting operational problems. One example is the large cogeneration plant that provides steam to an industrial plant and electric energy to the power system. The industrial-plant steam demand schedule sets the operating pattern for the generating plant, and it may be necessary for a utility to modify its economic schedule to facilitate the industrial generation pattern.

Transmission access for nonutility entities (consumers as well as generators) sets the stage for the creation of new market structures and patterns for the interchange of electric energy. Previously, the major participants in the interchange markets in North America were electric utilities. Where nonutility, generation entities or large consumers of power were involved, local electric utilities acted as their agents in the marketplace. This pattern is changing. With the growth of nonutility participants and the increasing requirement for access to transmission has come a desire to introduce a degree of economic competition into the market for electric energy. Surely this is not a universally shared desire; many parties would prefer the status quo. On the other hand, some electric utility managements have actively supported the construction, financing, and operation of new generation plants by nonutility organizations and the introduction of less-restrictive market practices.

The introduction of nonutility generation can complicate the scheduling-dispatch problem. With only a single, integrated electric utility operating both the generation and transmission systems, the local utility could establish schedules that minimized its own operating costs while observing all of the necessary physical, reliability, security, and economic constraints. With multiple parties in the bulk power system (i.e., the generation and transmission system), new arrangements are required. The economic objectives of all of the parties are not identical, and, in fact, may even be in direct (economic) opposition. As this situation evolves, different patterns of operation may result in different regions. Some areas may see a continuation of past patterns where the local utility is the dominant participant and continues to make arrangements and schedules on the basis of minimization of the operating cost that is paid by its own customers. Centrally dispatched power pools could evolve that include nonutility generators, some of whom may be engaged in direct sales to large consumers. Other areas may have open market structures that permit and facilitate competition with local utilities. Both local and remote nonutility entities, as well as remote utilities, may compete with the local electric utility to supply large industrial electric energy consumers or distribution utilities. The transmission system may be combined with a regional control center in a separate entity. Transmission networks could have the legal status of "common carriers," where any qualified party would be allowed access to the transmission system to deliver energy to its own customers, wherever they might be located. This very nearly describes the current situation in Great Britain.

What does this have to do with the problems discussed in this text? A *great*

*deal.* In the extreme cases mentioned above, many of the dispatch and scheduling methods we are going to discuss will need to be rethought and perhaps drastically revised. Current practices in automatic generation control are based on tacit assumptions that the electric energy market is slow moving with only a few, more-or-less fixed, interchange contracts that are arranged *between interconnected utilities.* Current techniques for establishing optimal economic generation schedules are really based on the assumption of a single utility serving the electric energy needs of its own customers at minimum cost. Interconnected operations and energy interchange agreements are presently the result of interutility arrangements: all of the parties share common interests. In a world with a transmission-operation entity required to provide access to many parties, both utility and nonutility organizations, this entity has the task of developing operating schedules to accomplish the deliveries scheduled in some (as yet to be defined) "optimal" fashion within the physical constraints of the system, while maintaining system reliability and security. If all (or any) of this develops, it should be a fascinating time to be active in this field.

## FURTHER READING

The books below are suggested as sources of information for the general area covered by this text. The first four are "classics;" the next seven are specialized or else are collections of articles or chapters on various topics involved in generation operation and control. Reference 12 has proven particularly helpful in reviewing various thermal cycles. The last two may be useful supplements in a classroom environment.


1. Steinberg, M. J., Smith, T. H., *Economy Loading of Power Plants and Electric Systems*, Wiley, New York, 1943.
2. Kirchmayer, L. K., *Economic Operation of Power Systems*, Wiley, New York, 1958.
3. Kirchmayer, L. K., *Economic Control of Interconnected Systems*, Wiley, New York, 1959.
4. Cohn, N., *Control of Generation and Power Flow on Interconnected Systems*, Wiley, New York, 1961.
5. Hano, I., *Operating Characteristics of Electric Power Systems*, Denki Shoin, Tokyo, 1967.
6. Handschin, E. (ed.), *Real-Time Control of Electric Power Systems*, Elsevier, Amsterdam, 1972.
7. Savulescu, S. C. (ed.), *Computerized Operation of Power Systems*, Elsevier, Amsterdam, 1976.
8. Sterling, M. J. H., *Power System Control*, Peregrinus, London, 1978.
9. El-Hawary, M. E., Christensen, G. S., *Optimal Economic Operation of Electric Power Systems*, Academic, New York, 1979.
10. Cochran, R. G., Tsoulfanidis, N. M. I., *The Nuclear Fuel Cycle: Analysis and Management*, American Nuclear Society, La Grange Park, IL, 1990.
11. Stoll, H. G. (ed.), *Least-Cost Electric Utility Planning*, Wiley, New York, 1989.
12. El-Wakil, M. M., *Power Plant Technology*, McGraw-Hill, New York, 1984.

13. Debs, A. S., *Modern Power Systems Control and Operation*, Kluwer, Norwell, MA, 1988.
14. Strang, G., *An Introduction to Applied Mathematics*, Wellesley-Cambridge Press, Wellesley, MA, 1986.
15. Miller, R. H., Malinowski, J. H., *Power System Operation*, Third Edition, McGraw-Hill, New York, 1994.
16. Handschin, E., Petroianu, A., *Energy Management Systems*, Springer-Verlag, Berlin, 1991.